Astro2020 APS White Paper

Planck-scale physics vs. Galactic astrophysics – addressing the need and requirements for the high-fidelity full-sky low-frequency microwave polarization survey to provide enabling support for the future CMB observations and their interpretation

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract:
We discuss the importance of addressing a persistent problem in the field of CMB observations and their interpretation – the imbalance between the achievable measurement quality at the very low ($\lesssim 20$ GHz) and high ($\gtrsim 300$ GHz) frequency ranges. These measurements are essential for cleaning Galactic foregrounds, extracting cosmological signals, and achieving the demanding scientific goals of the future inflation probe space mission to measure and characterize the primordial gravitational wave background related polarized CMB anisotropies. To achieve comparable angular resolution and noise as at high frequencies, low frequencies require larger telescopes and greater focal-plane area. This places extreme demands on a single-telescope mission. We stress the great need for future improvement of measurements at low frequencies, and we recommend study of a mission dedicated to those low frequencies, to determine whether such a mission, in combination with a higher-frequency mission, would be the most cost-effective way to obtain the low frequency data required by CMB science.

1 Introduction

Through decades of CMB measurements conducted suborbitally and by three space experiments – COBE, WMAP, and Planck – we have witnessed remarkable progress in the search for, discovery, and characterization of the cosmic microwave background (CMB) anisotropies. Precise measurement and interpretation of these subtle signals yielded a remarkable crop of scientific results, ranging from strong support for the so-called standard model of cosmology, with impressively precise parametrization, to CMB lensing by large scale structure in the Universe, tight constraints on isotropy and non-Gaussianity of primordial perturbations, measurements of the SZ effect in clusters of galaxies (i.e. inverse-Compton energy boost of CMB photons scattering off high-energy electrons in clusters; Sunyaev and Zel'dovich, 1972), physical characterization of emissions from our Galaxy and its magnetic field, and rich catalogs of sources from radio to submillimeter wavelengths, to mention a few (Planck Collaboration (c); Akrami et al., 2018, and references therein).

The ultimate target for current and future CMB observing efforts is the discovery and characterization of the relic gravitational wave background (GWB) from the very early Universe expected to exist according to the inflationary paradigm in cosmology (Shandera, 2019, and refs. therein). This GWB would induce additional (to that caused by density perturbations) temperature and polarization anisotropy in the CMB. Polarized CMB anisotropy patterns can be represented as a combination of gradient-like E-modes, sourced by both the density and gravity wave perturbations, and vorticity-like B-modes, which in the very early Universe can be sourced only by the GWB. Hence, the truly primordial B-mode anisotropy of the polarized CMB may allow us, through measurements of its overall amplitude and spatial structure, to infer the fundamental physical properties of the agents that made the Universe the way it is, e.g. the energy scale of inflation. Considering that it is less than 100 years since it has been established that the Universe is expanding, experimental determination that we understand the evolution of the Universe essentially since the Big-Bang would be a colossal triumph of science.

Originally the main thrust of CMB experiments was to measure temperature anisotropies, but for the last decade the emphasis has slowly shifted towards the measurement of polarized anisotropies. Cosmological GWB related signals encoded in polarization anisotropies are tremendously demanding targets for measurements. Primordial B-mode signals should be present on angular scales larger than a few degrees, with characteristic features at very large angular scales ($l < 10$, due to low redshift reionization), and at intermediate angular scales ($l \sim 80$, the recombination bump), with the overall power amplitude, usually expressed as a power ratio, r, of tensor (GWB related polarization anisotropy) to scalar (the familiar CMB temperature anisotropy) perturbations at very large angular scales ($l = 2$). Presently the best upper limit is $r < 0.07$ (95%) (BICEP2/Keck Collaboration: Ade et al. 2018). Future efforts aim at achieving a detection of GWB by reaching a sensitivity of $r \sim 10^{-3}$(LiteBIRD: Hazumi et al. 2019; CMB-S4 Collaboration: Abazajian et al. 2016, Barron et al. 2018; The Simons Observatory Collaboration, Ade et al. 2019), and $r = 5 \times 10^{-4} (5\sigma)$ with PICO (Hanany et al. 2019). Instruments capable of doing this will have to demonstrate extraordinary levels of sensitivity by reaching noise performance in the nK range. Remarkably, this is indeed planned for the flagship efforts like CMB-S4 on the ground, and PICO in space.

There are very many issues that will need to be addressed and resolved on the path to success in this program; excellent discussions of the subject are given in, e.g., Abazajian et al. 2016, Hanany et al. 2018, and Rocha et al. 2019. This paper focuses narrowly on a particular issue that persists in the landscape of CMB anisotropy measurement efforts, and, in our opinion, requires attention, as otherwise it may have an unwanted impact in the future. To paraphrase Karen Lamb, this paper is about avoiding this: "A year (or rather a ~decade, or so) from now you may wish you had started today."

2 What is the problem, and why is it hard?

CMB polarization anisotropies of cosmological origin are very faint; the already-detected E-mode anisotropy is typically at only a few per cent strength compared to the total intensity perturbations, and the yet-undetected B-modes are predicted to be much weaker still. All CMB polarization anisotropy at large angular scales is strongly dominated by foreground emission from our Galaxy, by thermal dust at high frequencies and synchrotron emission at low frequencies. Primordial CMB B-mode anisotropy is very strongly foreground-dominated at all angular scales, and will only be revealed if those dominant foreground emissions can be reliably removed from the maps of polarized sky.

Foreground emission, unlike the cosmological signals of interest, is not describable by any *ab initio* models. In order to remove foreground signals from the experimental data, one has to rely on their actual measurements, including at the lower and upper ends of the frequency range away from the foreground intensity minimum (70–90 GHz). There is a substantial body of ongoing work invested in the development and refinement of parametrized models of foreground emission that describe the already available data (e.g. Planck Collaboration (b), Ade et al., 2016, Planck Collaboration (d), Akrami et al., 2018, Remazeilles et al. 2016, Remazeilles et al. 2018), especially the dependence of foreground-emission SEDs on frequency. However, such models, due to their phenomenological underpinning, do not have true predictive power for those physical regimes still not subject to measurement (be it emission maps at frequencies not previously observationally constrained, or spatial resolution not yet reached by the already conducted experiments), and their usefulness is entirely determined by the quality of available input data.

Presently the only polarized full sky surveys available for assessment of foreground emission from our Galaxy are those by WMAP at low frequencies, and by Planck Low- and High-Frequency Instruments.

Planck-HFI has opened up a new window to the polarized CMB sky at four bands in the 100–353 GHz range. What we have learned is that dust emission phenomenology is complex, and may, in future experiments, require denser frequency coverage, higher angular resolution, and, obviously, sensitivity, to allow precision of its characterization on a par with the requirements set by cosmological B-mode signal extraction and analysis. Fortunately, these requirements are a natural design focus for the powerful future space instruments, like PICO, as their massive focal plane arrays are planned to be bolometric, highly sensitive, and coupled to optical systems allowing significant improvement over Planck in angular resolving power. Hence, the prospects for addressing sufficiently well the high-frequency foreground separation problems of the B-mode targeting experiment(s) with data collected by a single platform in space appear rather good. Ground based efforts have limited sky access at the upper frequency range due to the atmospheric transmission window, but can observe with greater angular resolution than space missions at the accessible frequency bands, which will help with further refinements of the overall dust foreground emission models. These refinements will be necessary, as there is currently a gap between those studying the magnetized interstellar medium (ISM) and the cosmologists attempting to exploit more fully the microwave and sub-mm data to detect the primordial B-modes. Planck Collaboration (e) (2018, and refs. therein) have demonstrated how the turbulent dust foreground affects both the ratio of E- to B-modes as well as the TE correlation. In order to detect the inflation signals, we need to understand these effects in the context of the turbulent ISM, how they affect both dust and synchrotron emission, and how they feed into the potential instrument systematics.

But the real focus of this discussion is on low-frequency polarized foregrounds, surveyed on the full sky by WMAP and Planck-LFI, the most important of which is synchrotron emission by the Galaxy. To zeroth order, the model picture is deceptively simple – a single emission mechanism with power law SED ($\sim\nu^{-3.1}$), and the spatial pattern of observed intensity (both total and polarized) dictated by the distribution of cosmic ray electrons and configuration of the Galactic magnetic field (GMF) along the line of sight. A more refined picture involves possible deviations from a simple power law SED expected if there are variations in the cosmic ray spectral properties throughout the Galaxy (e.g. the SED curvature), spatial variations in the overall spectral index, and also a possible presence of other polarized emission mechanisms with different SEDs, e.g. the anomalous microwave emission (AME) by spinning dust with an SED bump at the frequency range around ~30 GHz.

Indeed, the physical picture of the low frequency polarized Galactic emission is rather complex. The polarized diffuse synchrotron emission is dominated by the loops and spurs known from low-frequency surveys, with the diffuse emission being relatively weak. This is in contrast to the total intensity, where it is the broad diffuse emission that dominates the total flux, even though the Galactic plane and North Polar Spur are evident.

As measured from WMAP and Planck low frequency data, the synchrotron spectral index is steeper at high Galactic latitudes than along the Galactic plane (Kogut et al. 2007, Dunkley et al. 2009; Macellari et al. 2011, Fuskeland et al. 2014, Krachmalnicoff et al. 2018) with typical values of approximately -3 and -3.1, respectively. However, the spectral index is also steeper towards the Galactic center and anti-center compared to the spiral arms. Otherwise, given the large errors on the spectral index determination on patches of the sky, there is little detailed information on the variation of the synchrotron spectral behavior at high latitudes, or any associated morphology. Interestingly, one exception is a measure of the spectral index of a filament associated with the Fermi bubbles (Planck Collaboration (a); Ade et al. 2015) with a value of -2.5, much flatter than any of the values determined above.

Let us further illustrate the complexity of the problem by considering that modeling the GMF requires an understanding of the 3D statistical properties of the turbulent ISM and how they project onto a 2D sky map observed from within the Galactic disk. Efforts to improve this have only recently begun with, e.g., Kim et al. (2019), using MHD simulations, or Wang et al. (2019) using faster but less physically realistic methods. There is also a great deal that is not understood about how the spatial and spectral distribution of cosmic rays is affected by turbulence in the magnetic field, and this is crucial for understanding both the spatial and spectral distribution of synchrotron emission. It is known that the synchrotron spectral index varies on the sky (Fuskeland et al., 2014; Krachmalnicoff, et al. 2018), but the magnitude of the variations is not reproduced by current cosmic ray propagation models (Orlando & Strong, 2013). It is also not known observationally down to what angular scales these variations in the synchrotron spectrum are significant, a point that is important for component separation and in design of future experiments. Furthermore, the thermal dust and synchrotron emission processes are generally treated completely independently, because they come from different phases of the ISM. But they are affected by the same GMF on all scales, and cosmic rays, though more diffuse, are thought to penetrate dust clouds (Dickinson et al., 2015). Clearly, the field is replete with unanswered questions, and in need of improved observational data, which need we now turn to.

Low frequency observations can be conducted in space and on the ground. Let us address the issues particular to both options.

Designs for future space missions use a single telescope to illuminate a focal plane populated with detectors apportioned to the entire spectral range of the experiment. Consequently, the lowest frequency channels always are constrained to observe the sky with the poorest angular resolution. Further, foreground signals get brighter at lower frequencies, hence it is usually considered sufficient for the lowest frequency channels to operate at higher detector noise levels. Furthermore, low frequency detectors are large, and take up focal-plane space that could be filled with many more smaller ones at the higher frequency channels that are critical for maximization of the overall instrument's sensitivity to cosmological perturbations. These points invariably drive design toward minimization of the precious resources of the space instrument that are allocated to low frequency observations. The lowest frequency channels of WMAP and Planck (23 and 30 GHz, respectively) had just four detectors each, placed at the edge of the focal planes and subject, in addition to the points made above, to significant beam distortions. Again, all these considerations illustrate a specific issue to be confronted while designing a CMB space instrument: low frequency channels end up with the lowest resolution, high noise, and typically less favorable placement in the focal plane – and, they may still collaterally diminish performance of higher frequency channels by taking the valuable focal-plane space.

Still, the best available full sky polarized emission surveys generated to date are those of WMAP K-band, ~23 GHz, and Planck LFI 30 GHz. These maps are simply invaluable in component separation of the multi-frequency data. However, a close look reveals significant issues that affect these sky maps, and shows that improvements will be needed in future surveys to achieve the level of accuracy in component separation required for the B-mode search. In the subsection 2.1 below we give an example of consistency analysis of the WMAP and LFI low frequency sky maps.

Unlike the high frequency range that is unobservable through the atmosphere, frequencies below 45 GHz relevant for CMB foreground separation can be observed from the ground, with sizeable antennas. Hence it is often stated that the ancillary data for CMB foreground separation can be obtained with suborbital observations, considerably less costly than from space-based platforms. This is correct up to a point, but does not address the actual, extreme requirements on data quality that must be met to satisfy the needs of foreground separation in B-mode targeting experiments. Since the requirements for such surveys include multiple frequencies of observation, large or all-sky coverage, and extreme levels of sensitivity and systematic control, there are numerous difficulties to be resolved. The obvious issues are the limited sky availability for any given suborbital telescope (hence the need to stitch together heterogeneously-generated data, which requires extraordinary intercalibration accuracy), lengthy observing campaigns required to achieve the requisite survey sensitivities (while assuring measurement stability and calibration consistency), exquisite control of instrumental systematic errors (e.g., imperfectly known beam responses, including far-side lobes), sufficient shielding from ground pick-up, atmospheric effects, and RFI. Even though the need for quality low frequency sky surveys to support the CMB component separation is manifest, and declared to be less costly to conduct with telescopes on the ground, precious few efforts of this nature are being conducted. The relevant ongoing experiments are C-BASS (5 GHz, see e.g. Dickinson et al. 2019), S_PASS (~2.3 GHz, Carretti et al. 2019), QUIJOTE (10-20 GHz, Genova-Santos et al. 2015), and the forthcoming ones are AdvACT (~30GHz, Koopman et al. 2018), GreenPol (10-44 GHz, Fuskeland et al. in preparation), and SKA-MPG/S-band (1.7-3.5 GHz, Basu et al. 2019). All of these are spectacular, and very hard efforts, subject to difficulties listed above. Specifically, regarding the observed sky area, other than C-BASS that aims for aggregating measurements from two sites, at most about 50% of the sky can be surveyed by any of these experiments. Therefore, it is fairly safe to state that the prospect for a *full sky*, *uniformly high-quality* polarized radio survey, preferably at several frequency channels in the range of 2-20 GHz (advocated as the best range to target for Galactic synchrotron mapping in Planck Collaboration (e), 2016), are fairly slim, and we may not see such data products made available to CMB community even on a time scale of more than a decade.

2.1 A quick look at the WMAP and Planck LFI comparison at their lowest frequency channels.

WMAP K-band (23 GHz) and Planck (2018 release) LFI 30 GHz sky maps are currently the only available low-frequency, polarized full sky surveys. Figure 1 shows the polarization EE and BB pseudo-cross-spectra (cross- means evaluated between two different maps, and pseudo-means evaluated on a fraction of the sky) evaluated on the half-data split Stokes Q and U sky maps for LFI, and on the coadded yearly K-band maps (4 and 5 yearly Q and U map sets). Spectral phenomenology is as follows. The WMAP K-band is more noisy than LFI 30 GHz, but the Galactic synchrotron emission is brighter at the K-band by a factor of 2.28 (5.2 in the spectrum). Both data sets are noise dominated at $l > 100$. Polarized foreground E and B spectra are approximately power-law over the range where S/N>1, and the amplitude is somewhat higher in E than in B. Cosmological polarized CMB signals in these maps/spectra are massively dominated by noise at all scales.

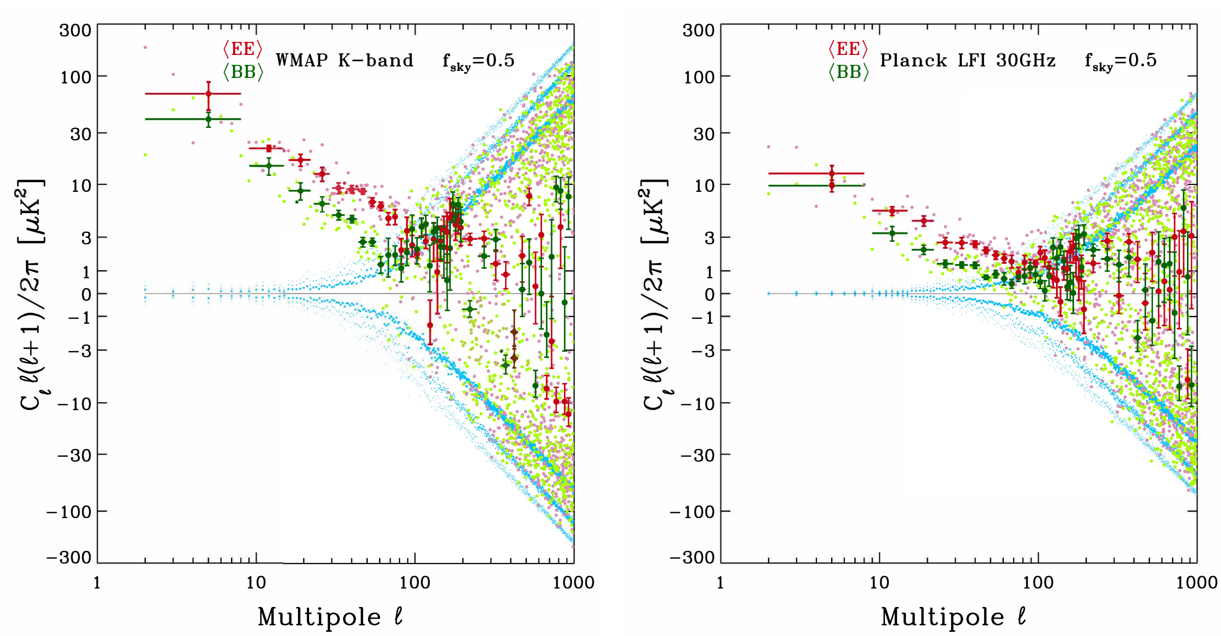

Figure 1. EE and BB pseudo-cross-spectra evaluated on Galactic polar caps at $|b| > 30$ deg, i.e. $f_{sky} = 50\%$, of the WMAP K-band and Planck LFI 30 GHz Q and U sky maps. EE/BB spectra are shown in pink/lime dots for all multipoles , and in red/green dots/bars for the values binned over the range of $\Delta l = 7$ (50) below (above) $l = 200$. Error bars indicate the rms spread within the respective bins. Three light blue bands indicate the 1, 2, and 3σ ranges of the distribution of cross-spectrum noise evaluated with the empirical model based on intrinsic data splits (half-ring maps for LFI 30 GHz, and 4, and 5 coadded yearly maps for WMAP K-band). Nonlinear vertical scale runs as log_{10} beyond ± 1 μK, and is nearly linear in-between.

Figure 2 shows maps of polarization amplitude for these data sets. These maps were smoothed to a common resolution of FWHM=4 deg in order to suppress the noise and make it easier to assess visually their consistency (formally these maps are strongly signal dominated, see the spectra at $l \lesssim 20$). In order to quantify the degree of consistency non-parametrically, i.e., without invoking any foreground emission model, we employ the Spearman-ρ rank-order correlation test (see e.g. Dickinson Gibbons and Chakraborti, 2015). The maps as shown are pixelized at ~7 arcmin scale. We divide them into 16x16 pixel subsets, run the Spearman-ρ in each one (12288 such sets on the full sky), and show the result in the lower-left panel. Spearman-ρ value range of ± 1 corresponds, for each 256-count set of pixel pairs that we are comparing, to $\pm 16\sigma$ significance range of ρ (w.r.t. the null hypothesis that the 256-pixel value sets are random). We reject those sets for which ρ is less than $+3\sigma$-significant, the highly negative (statistically significant) values as well, as they

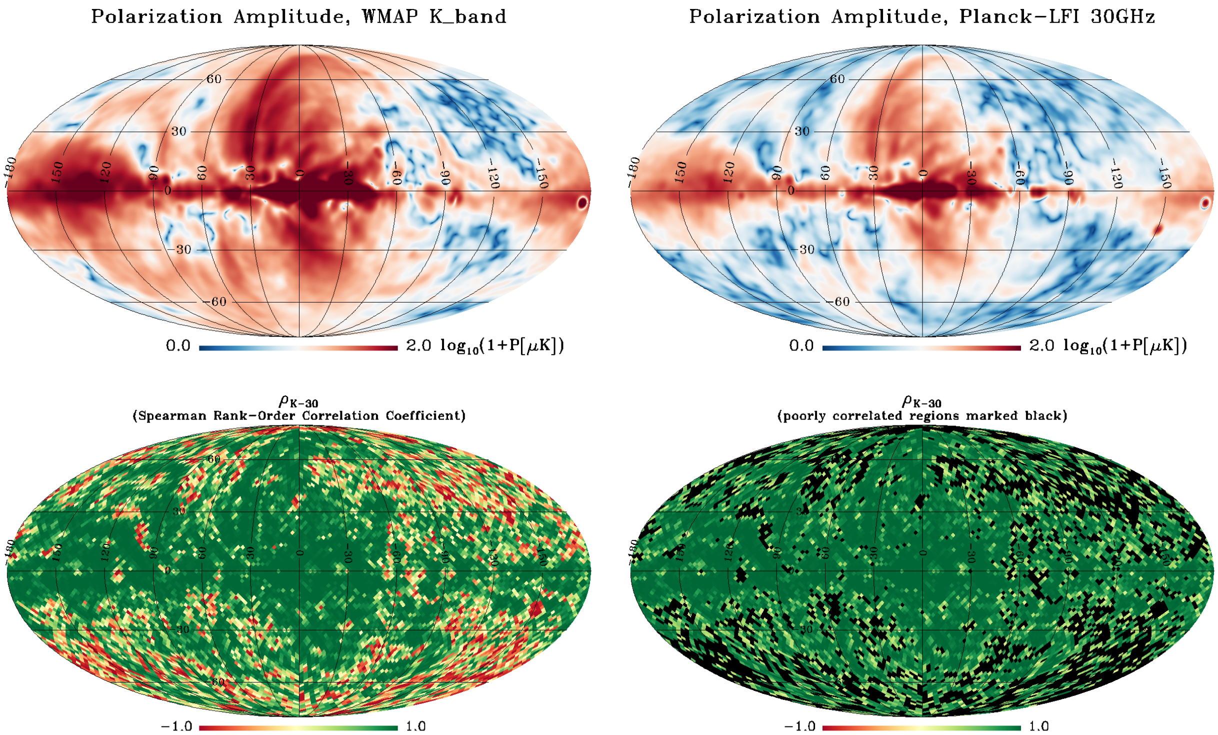

Figure 2. Non-parametric test, Spearman rank-order correlation ρ, of signal consistency for polarization amplitude of the WMAP K-band and Planck LFI 30 GHz channels. Upper panels: polarization amplitude (in μK) plotted non-linearly ($\log_{10}(1+P)$), and saturated at $P = 100\mu$K. The maps are smoothed to $FWHM = 4$ deg, and pixelized at 14 arcmin. Lower-left: Spearman rank-order correlation coefficient ρ_{K-30} evaluated within the large, 1.83 deg pixels, each comprising 16^2 original maps' small pixels. Lower-right: Regions where signal correlations are significant are retained, and those where ρ_{K-30} indicates either weak- or anti-correlation are masked in black. Sky fraction occupied by the poorly correlated regions is 23.5%.

correspond to strongly anti-correlated local pixel value distributions on these maps. We mask the rejected large pixels, and display the result in the lower-right panel. It is apparent that the regions of bright foreground emission display very high level of consistency (ρ really measures local phase consistency between the maps) – the total sky fraction of bad pixels is 22%. However, this is, of course, distributed unevenly; around the Galactic plane, at $|b| < 30$ deg, the bad pixel sky fraction is ~15%, but in the polar caps, at $|b| > 30$ deg, the bad pixel sky fraction is 32%. This is not good news; even at rather large scales (there are about 4 pixels, visible in the bottom panel maps, per smoothing kernel size of FWHM=4 deg) these heavily smoothed maps are not sufficiently consistent to warrant their joint use in component separation exercises with extrapolation of synchrotron emission patterns to higher frequencies.

3 What can be done about it?

Given the potentially bifurcated path to the necessary improvement of low-frequency measurements/sky maps that will be needed for sufficient support of the ultimate cosmological B-mode characterization work in the future – with either the ground observations, or a space mission to be the source of adequately high-quality data – two lines of advocacy have to be pursued.

Our purpose with this paper is to state the problem bluntly, so it is not treated in an offhand way. There is a great need for dedicated work in the area of improving understanding of the extreme needs for progress and dramatic change in the status quo of the low-frequency polarized foreground observations and their derived understanding, and there is a real danger of letting it linger until the "ultimate" space mission is designed and implemented.

Certainly, ground-based observations should be supported, helped, and encouraged to generate broadly disseminated results so the community can benefit from them, and learn and decide if such efforts will indeed provide sufficient support for the component separation needs of a mission like PICO.

However, given the known difficulties that persistently challenge ground-based efforts, our preferred line of advocacy is for the support to study the space mission option for generation of the survey of the polarized low frequency foregrounds. Our recommendations are as follows:

- Conduct a design study, driven by science requirements, for an optimized low frequency CMB polarimeter (neither WMAP nor Planck were designed to be that) to observe the full sky from the Lagrange point L_2, to generate sky maps at the frequency channels of ~2-20 GHz, and at angular resolution no worse than ~30 arcmin at 10 GHz. Target sensitivity for such polarized synchrotron emission measurements, and cost ramifications would be the objective of such a study.
- Study the options for launching of a large aperture telescope required for such experiment with a focus on the already available options for deployable radio antennas.
- Define requirements on a satellite bus that could provide support for a large aperture telescope, and power supply sufficient to support the required system cooling.
- Assess feasibility of mission strategy for operations at L_2 that would involve full sky scanning with a large aperture, continuously moving dish w.r.t. spacecraft dynamics, far side lobe pick up control, and experiment duration.
- Support continued development of advanced component separation methods and of the required inputs for realistic modeling and simulations of the foreground and cosmological signals – this must be done to assess realistically the necessities in the area of polarization measurement strategy and the actual quality demands at low frequencies that have to be met in order to support future efforts in cosmology and CMB polarimetry. Current state-of-the-art techniques addressing the inseparable challenges of simulation and separation of foregrounds are unlikely to be sufficient and should see dedicated and synergistic effort toward their improvement (as illustrated with the discussion of the necessary linking of the fields of CMB foreground simulation, Galactic magnetic field modeling, and CMB component separation).

4 If successful, what difference will it make?

If it were possible to generate high quality, full-sky, polarized maps of foreground emission at multiple low frequencies independently, and perhaps in advance of the powerful CMB polarization mission targeting primordial anisotropies (that could then more efficiently concentrate detection sensitivity between, say, 50 and 160 GHz, and observe at higher frequencies to measure adequately the polarized dust emission), a number of the following, serious advantages would be gained.

1) Present studies of future CMB instruments postulate deploying bolometric detectors across the frequency range down to 20 GHz in the case of PICO (but only down to 60 GHz in the case of LiteBIRD, which will have to rely critically on the ancillary data at lower frequencies). It is safe to say that significant technology demonstrations are required to ensure that this would indeed be possible. Relieving the instrument design from the requirement to use bolometers in that low frequency regime should be a simplification for the future CMB space mission focal plane development.

2) A related point is that a large fraction of the focal plane area of the future instrument(s) that presently is typically allocated to low frequency detectors would be freed up, and could be used for higher frequency detectors allowing very considerable sensitivity gains (many smaller high-frequency detectors to replace fewer, larger low-frequency ones in the relevant part of the focal plane); in case of PICO design study it is about ~20% of the focal plane area for the Tile type 1 detectors (21, 30, 43 GHz band centers), or ~50% for both Tile type 1 and 2 detectors (25, 36, 52 GHz band centers). **NOTE:** This point does NOT imply any criticism of PICO design study's vision of the focal plane layout; if there is no potential for provision of sufficiently good quality ancillary data at low frequencies prior to flight, PICO design concept is very powerful and very likely as good as can be conceptualized now; our point is, to rephrase it, that further optimization studies of PICO-type space mission would benefit from splitting the low and high frequency instruments between dedicated experiments.

3) Potentially fewer sources of systematic effects (fewer frequency channels) would need addressing in either effort - both PICO, and a dedicated low frequency experiment.

4) The opportunity for design optimization of the low-frequency polarimeter, including increasing the angular resolution and improving the optical performance, e.g., and most importantly, the symmetrization of beam response.

Given the systemic asymmetry between the low- and high-frequency polarized sky measurements that will be possible to conduct from a future single platform CMB space mission, e.g. PICO, it would be prudent to address the long standing and known problems at the low frequency range ahead of time to help the future inflation probe project become a true pinnacle of effort in observational CMB cosmology.

5 Acknowledgements

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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